The Air Bag System: What Went Wrong with the Systems Engineering?

Dennis M. Buede

Department of Systems Engineering, George Mason University, Fairfax, VA 22030-4444

Received January 16, 1998; accepted March 21, 1998

ABSTRACT

The air bag restraint system in automobiles has received a great deal of attention since the summer of 1996. The purpose of this paper is to review the successes and failures of the air bag from its introduction in 1988–1996 and to relate these successes and failures to the requirements that led to the current air bag design. The issue addressed in this paper is whether the systems engineering development process that led to the first generation air bag system could be considered reasonably successful. This question is not the same as whether the first generation air bag was better than no air bag system for the spectrum of drivers and passengers in automobiles and light trucks. Rather the issue is whether the first generation air bag system addresses the spectrum of requirements one could expect from such a system. Finally suggestions are made about how the requirements development process can be improved for all systems, considering the obvious and not-so-obvious mistakes that were made during the development of the air bag. ©1998 John Wiley & Sons, Inc. Syst Eng 1: 90–94, 1998

1. INTRODUCTION

Air bags are safety devices that are used in conjunction with safety belts. In particular, air bags installed in the steering wheel and passenger side dashboard are useful in frontal accidents that cause the driver and passenger to move forward toward the steering wheel or dashboard and windshield.

1.1. The Year Is 1983

You have been selected to be part of the systems engineering team for a new safety system to be installed on automobiles, called air bags. You are part of the requirements development effort. The systems engineering team consists of people from government [National Highway Traffic Safety Administration (NHTSA), which is part of Department of Transportation (DOT)] and industry. As background information you find that air bag research has been underway by automobile manufacturers for about 20 years. A 1969 research paper by General Motors [Brown and Skrzycki, 1996a] and a 1974 study by Volvo [Payne, 1996] both concluded that children and small adults were subject to injury or death during air bag inflation. General Motors actually sold cars with air bags in them from 1974 to 1976, but stopped the experimental program. There are currently about 30,000 people dying each year as occupants in accidents involving passenger cars and light

© 1998 John Wiley & Sons, Inc. CCC 1098-1241/98/010090-05

Table I. Yearly Fatality Data

Year	1983	1988	1995
Vehicle miles traveled (VMT, billions)	1700 (estimate)	2000	2400
Fatalities (passengers & drives)	30,000	34,000	32,000
% Frontal crashes	60+	60+	60+
% Seat belt use	10–15	25–40 (estimate)	65–70
Fatalities per billion VMT	18	17	13

trucks (see Table I). Over 60% of these fatalities occur in frontal accidents [Traffic Safety Facts 1995—Overview, 1996]. Only 10–15% of drivers and passengers are wearing their seat belts [Steed et al., 1996].

1.2. The Year Is 1988

Driver-side air bags are just now being introduced ahead of the government time line due to market forces. There are now about 34,000 people dying each year as occupants of passenger cars and light trucks; over 60% of the deaths involve frontal accidents. Seat belt use has grown substantially [Traffic Safety Facts 1995 — Overview, 1996]. There has been a great deal of discussion about air bag effectiveness since 1984, but the requirements have not changed in this time period.

1.3. The Year Is 1995

Air bags have been available for 8 years. During 1995 about 32,000 people died as occupants of passenger cars and trucks; over 60% of the deaths involve frontal accidents. Figure 1 shows a breakdown of traffic fatalities by age group; while the age groups are not equal in size, note the small percentage of fatalities for ages 1–15. Seat belt use has grown to between 65% and 70% [Traffic Safety Facts 1995 — Overview, 1996]. The 1984 requirements regarding safety and air bag design are still in effect.

More than 20% of cars on the highway in 1996 have air bag systems. Not only are air bags available on the driver's side, but also on the passenger's side. Last year air bags were credited with saving 475 lives, compared to 9800 lives saved for seat belts and 279 for child restraints [Traffic Safety Facts 1995 — Occupant Protection, 1996].[1] An analysis just released by NHTSA concludes that air bags are 30% effective in reducing fatalities in purely frontal crashes; 34% for unbelted drivers (who are a higher risk) and 21% for belted drivers. The safety effects of air bags for passengers in the front seat are similar [NHTSA, 1996].

However, by the end of October 1996 air bags were also responsible for killing 46 people, 28 children riding as front seat passengers and 18 drivers.[2] The rate of air bag related deaths has grown proportionately with their presence on the highway. Fifteen of the drivers were women between 4 ft 8 in. and 5 ft 5 in. tall. Nine of the drivers suffered brain or spinal injuries, just as the children who died; at least two of these nine drivers were wearing their seat belts. Most, if not all, of the children were either in rear facing safety seats or not properly belted. However, a number of these deaths occurred in accidents that occurred at 10 mph or less [Associated Press, 1996]. Note that air bag related deaths for children clearly do not occur in the same proportion as all traffic fatalities.

In addition, it is estimated [Frame, 1996] that 43% of air bag deployments cause some type of injury; 1% are serious and involve heart lacerations, lung contusions, or rib fractures; 3% are moderate (fractures and contusions). A broken right arm, a common injury, is the result of a driver turning left when the frontal

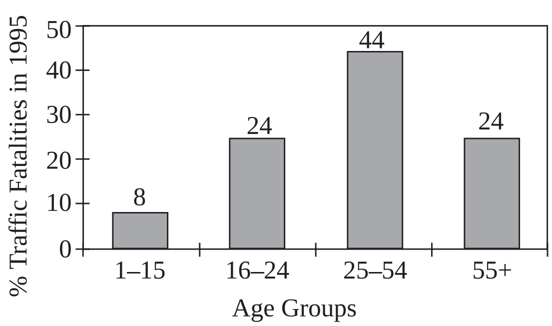

Figure 1 1995 traffic fatalities by age group.

[1] Lives saved are estimated based upon a sample of all traffic accidents. A judgment has to be made for each accident in the sample concerning whether a fatality would have occurred without the presence of the safety measure.

[2] Just as is the case for estimating lives saved, a judgment has to be made about whether the person would have been killed in the accident if the air bag had not been present.

accident occurs and having her/his right arm in the path of the air bag.

1.4. Would You Consider Your System To Be Successful?

Clearly, every safety device has the potential to inflict damage. Joan Claybrook, a central ex-government official in the history of air bag development, stated in a 1978 speech:

> Nearly every automotive system has some element of risk, and some limitation on its effectiveness. Safety belts, for example, are acknowledged to be superior crash protection devices, but their use occasionally results in injury from forces being concentrated on a vulnerable part of the body. Nevertheless, the tradeoff in terms of saving thousands of lives clearly outweighs these extraordinary and infrequent risks [Brown and Skrzycki, 1996b].

There is little room to disagree about seat belts. Seat belts save thousands of lives each year and at most cause minor to moderate injuries in the most severe accidents.

The numbers for air bags are quite good, but *can we conclude that the systems engineering process that produced the above results was acceptable?* I think not. While hundreds and eventually thousands of lives are being saved each year, many people are dying or being severely injured in accidents that they would otherwise have easily survived. In addition, the distribution of deaths due to air bags is skewed to specific portions of the population that should have been addressed in the air bag requirements, but were not.

In the discussion that follows, the systems engineering issues associated with the design and testing of the current air bag system will be addressed. (This paper will avoid issues related to the role of government in safety prevention, leaving that to discussions of political philosophy.) The roles that NHTSA and the automobile manufacturers played in reaching the current situation will also not be addressed. The focus here is on the requirements produced by the systems engineering process.

2. WHAT WENT WRONG?

The current air bag system contains four components: sensors designed to detect a frontal accident, a microprocessor, a polymer bag that is inflated, and a gas generator [The Chemistry . . . , 1996]. Current air bag systems use mechanical sensors consisting of a stainless steel ball that is held at one end of a closed cylinder by a magnet [Mahmud and Alrabady, 1995]. Any accident that causes the stainless steel ball to break free of the magnetic force will result in an inflated air bag. The stainless steel ball rolls down the cylinder and closes an electric circuit. Presumably, the harder the impact, the faster the steel ball moves down the cylinder and closes the circuit. Once the circuit closes, the gas generator electrically ignites a mixture of sodium azide (NaN_3), potassium nitrate (KNO_3), and silicon dioxide (SiO_2), creating enough nitrogen gas to fill the bag [the Chemistry . . . , 1996]. With this design the airbag has a single inflation rate of 200 miles per hour (mph). Inflation takes only 25 ms [Payne, 1996]. For this design to inflict little or no injury to the person being saved, the person must bump into a fully inflated air bag. If the air bag inflates into the person, severe injury can occur, especially for smaller, more fragile people.

The following requirements are paraphrased from those published in 1984 by NHTSA as part of Federal Motor Vehicle Safety Standard 208, Occupant Crash Protection.

1. The requirements defined a single safety scenario on which to base the design. This single scenario could only be justified if it was the worst case situation. Note that this was not the approach with seat belts, for which requirements were defined for the 50th percentile six years old, 5th percentile adult female, and 95th percentile adult male.
2. The single, worst case scenario for safety protection was the 50th percentile male not wearing a seat belt. No specific attention was directed towards children and women, and small or large adults. As the debate shows, this is the root of the problem.
3. The 50th percentile male was defined using World War II data on males entering the Armed Services [Powell, 1996]. Based on World War II data the 50th percentile male is 5 ft 9 in. and 165 lb.
4. While there was a requirement that the air bag not deploy on a very rough or bumpy road or when the car hits a small pole, there was no requirement that the air bag remain undeployed during accidents at sufficiently slow speeds that no lives are in danger. A number of people have lost their lives in accidents during which the air bag should not have deployed. My son tells me that in the early 1990s teenagers would commonly wander through parking lots and trigger air bag inflation by hitting a car's front bumper with a base ball bat.
5. The test condition was defined such that the test dummy is only in an upright position with its hands at the 3 and 9 o'clock positions on the steering wheel, and a frontal accident with the crash force parallel to the length of the car occurs

into a fixed barrier at 30 mph. In fact, frontal accidents are likely to occur when the driver is not in this nominal driving position. Also there are many accidents requiring an air bag safety restraint in which the crash force is close to being parallel to the length of the car but is not exactly parallel.

6. There was no requirement that addressed accidents involving preimpact braking. For frontal accidents, preimpact braking is common. In the case of the current air bag design, preimpact braking clearly causes problems because the people being protected are beginning to move towards the air bag before the sensors for activating the air bag can be triggered. This leads to a need for even more rapid inflation of the air bag.
7. The issue of injuries inflicted on drivers and passengers when the person collides with the deployed air bag was not addressed in the safety standard. Such a requirement would lead to an evaluation of the elasticity of alternate fabrics for the air bag, as well as the final pressure in the inflated air bag. The current fully inflated air bag is very inelastic.
8. There was no requirement that the disposal of unused or partially expanded air bags be safe and free of toxic waste. Sodium azide is considered a hazardous chemical by some [Engineering Design Home Page, 1996]. Also, uninflated air bag systems can explode when the car is crushed in a junkyard.
9. The requirements for air bags were placed in a federal regulation. It takes 16 months on average to change these regulations [Air Bag Safety Hearing, 1996]:

From 1970 until 1991, federal statutes requiring air bags were debated, imposed, revoked, and reinstated as consumer and safety groups battled it out with reluctant automobile manufacturers and mostly Republican administrations. It took a Supreme Court decision in 1983, overturning a Reagan administration revocation of the standard, before the campaign took on real momentum [Ottaway, 1996].

Unfortunately, while so much attention was being paid to the concept of air bags, the requirements for the air bags were overlooked and remained unchanged.

3. WHAT SHOULD WE LEARN

1. Never assume we know the worst case safety situation prior to the system's design. Pick a full range of possible worst cases.
2. Never assume the worst case is in the middle of the distribution of potential users. This is just common sense.
3. When recent data are not available for the distribution of potential users, use expert judgment, or a survey, not data that are 50 years old.
4. Cover the entire range of system scenarios and develop requirements for how the system should respond for all such scenarios. We should examine the system's interaction with other systems by such techniques as process and behavior modeling [Buede, in press; Charbonneau, 1996].
5. Make sure that actions the system should not perform are addressed, as well as those that the system should perform.
6. When humans are involved, do not assume that the human will perform according to some script or follow directions perfectly. Humans find many unexpected ways to use a system. Accidents with nuclear and other power plants are other examples of this very important lesson learned.
7. Specifically seek out potential victims of the system and view the impact of the system on them. Similarly, examine all possible side effects that the system might have.
8. Always consider the retirement of the system and its impact on the environment.
9. Do not employ an overly rigid requirements modification process. Requirements should change with our understanding of the system's environment. The environment in which most systems are used can change. Also technology advancement is changing too rapidly to freeze the requirements.

4. CONCLUSIONS

Air bags are saving lives. However, the design does not adequately take into account either the full spectrum of drivers and passengers or the human activities of these people while traveling in a car. This is directly traced back to the requirements. The requirements also do not address the full range of transportation situations in which people should be protected by a safety system such as an air bag. We are left with the clear conclusion that the systems engineering process for air bags was a failure.

This paper has provided lessons that we should learn from this failure. Let us hope that as the discussion about air bags continues, it begins to focus on changing the requirements, rather than jumping to a band-aid solution. Otherwise we run the risk of additional unforeseen consequences. Perhaps we will find that there are non-air-bag solutions that are even better than any air bag design.

REFERENCES

Air Bag Safety Hearing, House Appropriations Subcommittee on Transportation, 18–19, December 1996.

Associated Press, "Data: Smaller Women Vulnerable to Air Bags," *USA Today*, October 25, 1996.

Brown, W., and Skrzycki, C., "U.S. Doubts on Air Bags Date to '69," *Washington Post*, November 21, 1996a, p. A1.

Brown, W., and Skrzycki, C., ". . . the Claybrook Speech," *Washington Post*, December 13, 1996b, p. A23.

Buede, D. M., "Developing Originating Requirements: Defining the Design Problem," *IEEE Transactions on Aerospace and Electronic Systems*, Vol. 27, Part A, No. 5, September 1997, pp. 569–577.

Charbonneau, S., "Generation of Originating Requirements: Use of Functional Decomposition and State Transition Diagrams," unpublished M.S. thesis, George Mason University, 1996.

The Chemistry behind the Airbag, http://www.chem.uky.edu/courses/che115/airbag.htm

Engineering Design Class Home Page, University of Virginia, http://faraday.clas.virginia.edu/~ky4h/ed9/

Frame, P., "Crash-Test Changes Seen as Airbag Safety Solution," *Automotive News*, March 18, 1996, pp. 1, 8.

Mahmud, S., and Alrabady, A. I., "A New Decision Making Algorithm for Airbag Control," *IEEE Transactions on Vehicular Technology*, Vol. 44, No. 3, August 1995, pp. 690–697.

NHTSA, "Air Bags Reduce Driver Fatalities by 11 Percent," NHTSA 74-96, National Highway Traffic Safety Administration, Department of Transportation, Washington, DC, October 3, 1996.

Ottaway, D. B., "A Safety Device with a Fatal Flaw," *Washington Post*, October 2, 1996, pp. A1, A8–A9.

Payne, H., "Mandate That Morphed into a Killer," *The Washington Times*, December 22, 1996, p. B4.

Powell, M., Insurance Institute for Highway Safety, personal communication, November 27, 1996.

Steed, D., Curry, J. R., and Blakey, M., "The Air Bag Battle . . . ," *Washington Post*, December 13, 1996, p. A23.

Traffic Safety Facts 1995—Overview, NHTSA, http://www.nhtsa.dot.gov

Traffic Safety Facts 1995—Occupant Protection, NHTSA, http://www.nhtsa.dot.gov.

Dennis Buede is an Associate Professor of Systems Engineering at George Mason University. He teaches courses in systems engineering design and integration and multisensor data fusion and conducts research for the Center of Excellence in Command, Control, Communications and Intelligence. Dr. Buede is the Chairman of the Education and Research Technical Committee of INCOSE. His Ph.D. and M.S. are in Engineering-Economic Systems from Stanford University. He has a B. S. in Aerospace Engineering from the University of Cincinnati. Dr. Buede has had experience in the consulting industry, including starting and operating a consulting company that specializes in applications and research of decision analysis to systems engineering problems, decision support systems, and multisensor data fusion.